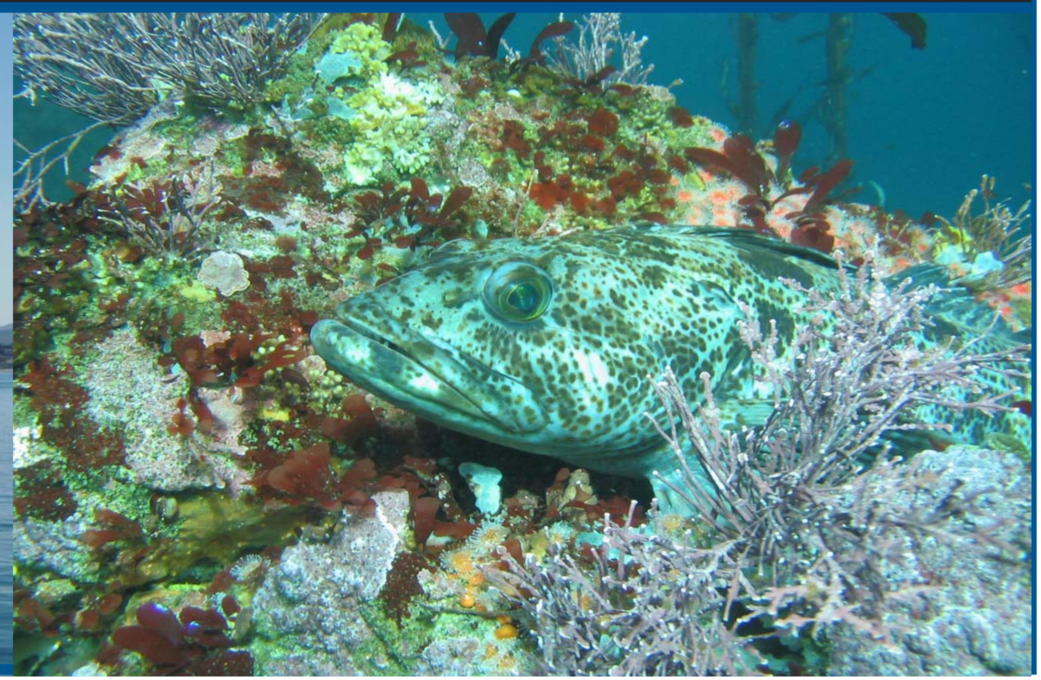
# Atlantis Ecosystem Model

## A decision support tool for ecosystem based management

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE



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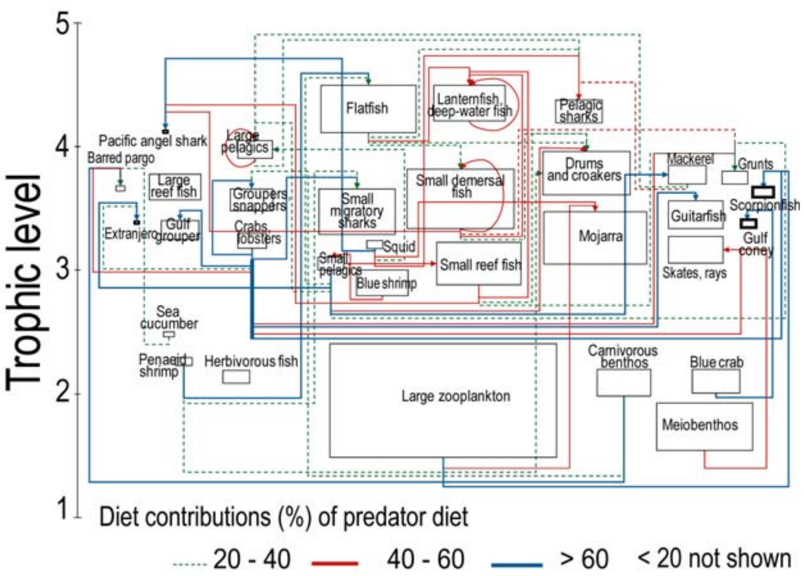
# What is the Atlantis ecosystem model?

The Atlantis ecosystem model ('Atlantis') is a flexible, modular modeling framework capable of producing realistic simulations of ecosystem dynamics. Atlantis serves as a strategic management tool capable of exploring ecological hypotheses, simulating climate scenarios, and testing human impacts on the environment including fisheries, changes in land use, non-point source pollution, and the effect of wind and wave farms. The Atlantis code base was developed by scientists at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia (Fulton 2004, Fulton et al. 2004). Atlantis integrates physical, chemical, ecological, and fisheries dynamics in a spatially-explicit, three dimensional domain.




Food web interactions for the Northern Gulf of California used to parametrize an Atlantis ecosystem model (Ainsworth et al. 2010). In Atlantis, the user can choose the level of complexity – from a few groups with simple trophic interactions and a simple catch equation to extensive models, with complicated stock structure, multiple fleets, detailed economics, and multiple management actions. This flexibility and mechanistic basis is parameter-intensive, making validation time consuming and precluding a full quantitative handling of parameter uncertainty.

As of 2011, there were 13 Atlantis models in use in Australia and North America; there are several others (7+) under development. Atlantis is an ideal tool for management strategy evaluation, where management policies and assessment methods are tested against simulations that represent a real ecosystem and its complexities; it is not intended to replace traditional stock assessments or to make short-term tactical decisions (i.e. total catch limits). The framework's code base simulates ecosystem dynamics, solving a set of differential equations on a 12 hour time step.

## Key ecological options and assumptions in Atlantis

These include density dependent movement, with predators moving toward areas with higher food availability; forced migrations into and out of the model domain (e.g. for highly migratory species such as whales); reproduction based on options including Beverton Holt stock recruitment relationships (for fish) and fixed offspring/adult (for mammals and birds). Predation can be governed by a modified Holling Type I, II, or III functional response with gape limitation, allowing predator diets to vary in relation to prey availability and prey length relative to the predator's length. Weight-at-age is dynamic, meaning that realized consumption rates throughout the modeled time period translate into variable weight-at-age of each cohort. Primary production is influenced by temperature, light, and nutrient availability, with nutrients and plankton advected by current fields. Atlantis functional groups include vertebrate, invertebrate, primary producer and three non-living groups. The model uses nitrogen as a common currency between groups. Silica is also handled dynamically, as is oxygen, although rudimentarily.

# Ecosystem dynamics in Atlantis are represented by sub-models

## Assessment and policy decisions

This module simulates data collection from the fishing industry and research surveys. This data is based on outputs from the biophysical and exploitation submodels, given a user-specified monitoring scheme and realistic assessment models or ecological indicators.

## Human activities

This module is focused on the detailed dynamics of fishing fleets (Case Study 2), but considers the impact of pollution, coastal development, and broad-scale environmental change. It allows for multiple fleets, each with its own characteristics (gear selectivity, habitat association, targeting, effort allocation and management structures). At its most complete, this module emphasizes dynamic fleets and catch-shares quota trading predictions. It can include explicit handling of economic drivers, compliance decisions, exploratory fishing, and other complicated real world concerns.

## Oceanographic

### Climate and hydrology

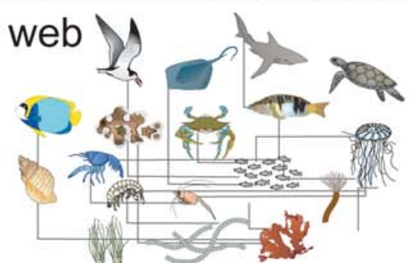
This module simulates fluxes of water and nutrients driven by temperature and salinity. Atlantis can represent persistent oceanographic processes such as a latitudinal gradient in turbidity, the natural stratification of salinity and temperature, and ocean circulation.

## Biophysical

This module tracks nutrient flows (usually nitrogen and silica) through the main biological groups found in the system and considers a variety of primary ecological processes: consumption, production, waste production and cycling, migration, predation, recruitment, habitat dependency, and mortality. Atlantis treats invertebrate groups as biomass pools (though cephalopods and prawns may have some age structure), while the vertebrates are represented using an age- and stock-structured formulation.

Atlantis is spatially-resolved in three dimensions using a realistic representation of the simulated marine system. The physical environment is represented through a series of polygons that coincide with the main geographic and regional characteristics of the marine system. The ecological processes are repeated in each of the depth layers within each polygon.

Food web



Biogeochemistry

Habitat

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# Model equations

## Primary producers

Primary producers are modeled as an aggregated biomass pool in each spatial box (i.e. a single depth layer of a polygon). The model tracks density (mg N/m$^3$) per box. Biomass growth is limited by nutrient, light and space availability. Biomass is lost to predation, lysis, and linear and quadratic mortality. Linear mortality represents additional density-independent mortality not explicitly modeled. Quadratic mortality represents density-dependent mortality (for instance, self-shading). Rate of change for a standard water column (*w*) primary producer (*PX*) is

$$\frac{d(PX_w)}{dt} = G_{PXw} - M_{lys,\,PX} - M_{lin} - M_{quad} - \sum_{i = \text{predator groups}} P_{PX\,w,\,i} \qquad G_{PX} = \mu_{PX} \cdot \delta_{irr} \cdot \delta_N \cdot \delta_{space} \cdot PX$$

Where $G_{PX}$ stands for the growth of *PX*, $M_{lys,PX}$ is the loss due to lysis, $M_{lin}$ and $M_{quad}$ are loss due to linear and quadratic mortality, $P_{PXW,\,i}$ are the losses of *PX* due to predation by *i* species, $m_{PX}$ is the maximum growth rate, $\delta_{irr}$ is light limitation, $\delta_N$ is nutrient limitation , and $\delta_{space}$ is space limitation.

## Invertebrates

Invertebrates are modeled as aggregated biomass pools in each spatial box. The model tracks density (mg N/m$^3$) per box, based on growth, predation, and linear and quadratic mortality. Quadratic mortality represents density dependent effects (predation, disease) that are not explicitly modeled. Rate of change for a standard invertebrate consumer (*CX*) is

$$\frac{d(CX)}{dt} = G_{CX} - M_{lin\,CX} - M_{quad\,CX} - \sum_{i = \text{predator groups}} P_{CX,\,i} - F_{CX} \qquad G_{CX} = \Big[\varepsilon_{CX} \cdot \sum_{i = \text{living prey}} P_{i,\,CX} + \sum_{j = DL,\,DR} (P_{j,CX} \cdot \varepsilon_{CX,\,j})\Big] \cdot \delta_{space} \cdot \delta_{O2}$$

where $G_{CX}$ is growth, $M_{lin\,CX}$ and $M_{quad\,CX}$ are linear and quadratic mortality, $P_{i,j}$ is predation by group *j* and group *i*, and $F_{CX}$ is fishing on this group. $e_{CX}$ is the growth efficiency of *CX* when feeding on live prey, $e_{CX,j}$ the efficiency when feeding on detritus (*DL* treated separately to *DR*), $\delta_{space}$ is space limitation, and $\delta_{O2}$ is oxygen limitation.

## Vertebrates

Atlantis tracks abundance, biomass, weight-at-age, and condition (reserve weight/structural weight) of each group through time, in each 3-d box and for the entire model domain. Each functional group has 10 age classes; these classes represent different phases in the lifecycle, so that for some groups it may be one year while for other (long lived) groups it could represent a decade or more.

# Model equations

For each age class and each spatial box, the model tracks the number of individuals and their average structural weight (bones and hard parts) and reserve weight (soft tissue). Growth and abundance are functions of recruitment, predation, consumption, and linear and quadratic mortality. Using the characteristics of vertebrates, some crude metrics of model performance can include: 1) comparing model-predicted values for structural and reserve weight relative to expected values, with expected values from von Bertalanffy growth parameters (for weight at age), 2) comparing predictions made to stock assessments (for unfished abundance). The rate of change for a vertebrate group (FX) is:

$$\frac{d(FX_{i,s})}{dt} = G_{FX_{i,s}} \qquad \frac{d(FX_{i,r})}{dt} = G_{FX_{i,r}} \qquad \frac{d(FX_{i,d})}{dt} = T_{IMM,FX_i} - T_{EM,FX_i} - M_{lin,i} - M_{quad,} - \sum_{j = \text{predator groups}} P_{FX,j} - F_{FXi}$$

where the subscript $i$ represents age group $i$ (there is one equation for each age class included), s stands for structural weight, r for reserve weight, and d for density. The $T$ terms represent the movement of fish in to ($T_{IMM,Fxi}$) and out of ($T_{EM,Fxi}$) the cell. The growth ($G$) for each vertebrate group is calculated by equations similar to those for invertebrates, but per age group of each vertebrate. The result is then apportioned to structural and reserve weight, favoring replenishment of reserves when the animal is underweight.

An ‘availability matrix’ describes the rates of flow of material between functional groups, by defining the contribution of each prey type to the diets of predators and considering density dependent effects relating to interaction rates, predator feeding mode, prey avoidance behavior and other factors.

## Nutrients

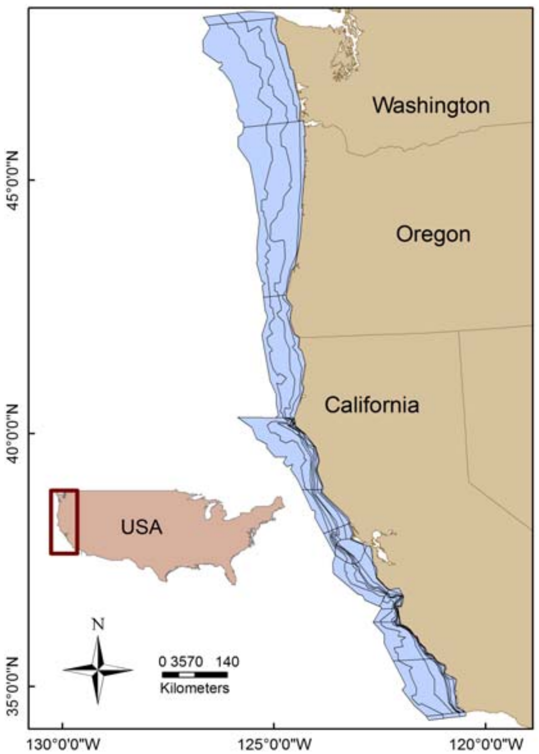
Water column nitrogen (ammonia and nitrate) concentrations are governed by uptake by autotrophs, excretion by consumers, nitrification, and denitrification. Rates of change for ammonia (NH) in the water column is:

$$\frac{d(NH_W)}{dt} = \sum_{i = PX_W} P_{NH_W,i} - P_{NH_W,MB_W} - P_{NH_W,MA} - P_{NH_W,PFB} + \sum_{i = CX_W,BF} E_i + \sum_{i = FX} E_i + \sum_{i = \text{pelagic bacteria}} E_i - S_{NIT,PAB} + R_{NET,w}$$

where $P_{N,XX}$ is the uptake of NH by the autotrophs (either generic, microphytobenthos MB, or macroalgae MA) , $E_{CX}$ is the production of NH by the consumer CX, $S_{NIT,XB}$ is the amount of NH converted to NO during nitrification by the bacteria XB, $R_{NET}$ is the amount of NH produced by denitrification.

Full descriptions of the dynamics of other forms of nitrogen, silica, bacteria, detritus, and sediment chemistry, as well as specialized parameterizations for dinoflagellates and macrophytes are contained in Fulton (2004, 2004b).

# Model processes




Extent of the Atlantis US West Coast model. Spatial resolution of the model represents ecologically important gradients and boundaries (i.e. biogeography, bathymetry), reflects stock assessment and catch data organization, and delineates existing and proposed management boundaries, in the form of polygons or boxes. These polygons allow the model to capture critical dynamics while being computationally efficient. Each polygon is further divided into water column depth layers and sediment layers.

## Oceanography

Atlantis employs a physical oceanographic model that drives bottom-up forcing of the system. Water movement, heat and salinity flux across boundaries are usually represented by a coupled regional ocean modeling system (ROMS; www.myroms.org) model. ROMS is an ocean circulation model that features a unified treatment of surface and bottom boundary layers and an integrated set of procedures for data assimilation.

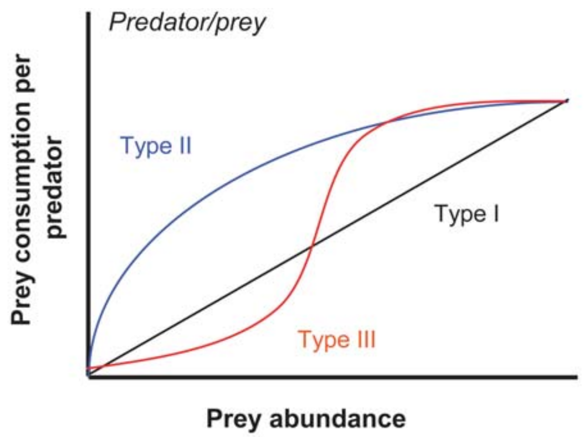
Ocean currents across each box face advect nutrients and have direct impacts on nutrient availability (ammonia [$NH_3$] and nitrate [$NO_3$]) to primary producers; the velocity and direction of ocean currents also influence the spatial distribution of planktonic groups. Temperature fields from the physical model influence biological processes such as respiration and spawning. Salinity can also be included in the physical model and optionally linked to biological processes. Hydrodynamics affect advection of planktonic groups, nutrient concentrations, and waste cycling. Temperature influences the respiration rate of each biological group in Atlantis; each group also has a defined thermal tolerance and a narrower thermal range for spawning. Current velocities across each box face advect nutrients and plankton groups, directly affecting nutrient ($NH_3$ and $NO_3$) availability to primary producers.Hydrodynamic forcing allows testing of the impacts that climate-driven changes in upwelling or coastal currents have on nutrients and primary productivity.

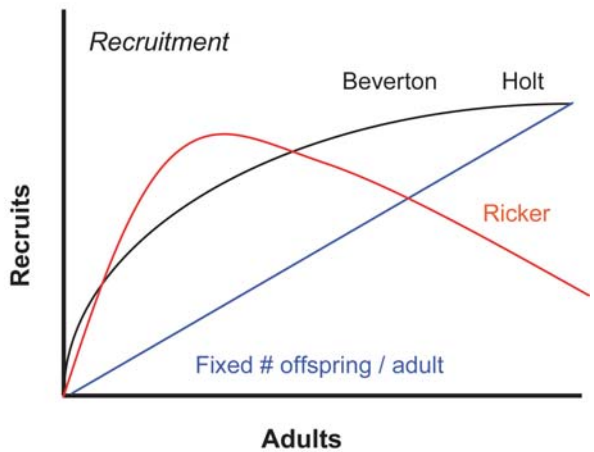
## Habitat associations

Habitat types in Atlantis include both physical and biogenic habitats. Physical habitats can include substrate types and geographic features such as canyons and seamounts. Biogenic habitat types examples include kelp, seagrass, and types of benthic filter feeders. Habitat associations are defined for each functional group.

## Movement

Atlantis simulates movement of individuals at two scales. Within the model domain, movement can be either density dependent or independent (i.e. seasonal migrations). Atlantis can also simulate larger migratory events where functional groups can leave the model extent.




## Predation

Growth of vertebrates follows von Bertalanffy growth parameters, but varies with consumption. Alternative feeding functional responses exist within Atlantis, including Holling functional response type I, II and III, or size specific Holling type III, and a bounded functional response (see Fulton et al. 2003).

## Spawning and recruitment

Reproduction can be modeled in two distinct phases in Atlantis. For each functional group, spawning occurs over a specific time window, and the materials (nitrogen) required for reproduction are removed from reserve nitrogen pools, which includes both gonadal and somatic tissue, such that parental weight-at-age declines. After spawning, each age class is incremented by one year, and a fraction of the oldest class dies.

Recruitment into the population follows at a specified time after spawning, and new recruits are then assigned to the first age class. The lag time between spawning and recruitment represents larval settlement time for fish, incubation period for birds, and gestation period for mammals. Recruitment can be based on many alternative relationships, Beverton Holt dependent on maternal condition, constant, lognormal, dependent on primary producers (Chl*a*), dependent on all plankton, Beverton Holt with lognormal variation added, linearly dependent on maternal condition, or forced timeseries of recruitment

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# Model calibration

Atlantis projects differential equations forward in time, based on a set of ecological parameters and initial conditions (biomasses, weights-at-age, and numbers-at-age). Unlike statistical models such as stock assessments, Atlantis does not use automated optimization algorithms to estimate parameters within the model; instead, parameters are derived outside the model before beginning a simulation. However, an iterative process can be used to tune or calibrate the model, adjusting parameters to reproduce more ecologically reasonable dynamics and to fit historical observations. This type of qualitative parameter adjustment is labor intensive, but gives the modeler a strong understanding of the key parameters and sensitivities in the model.

Iterative calibration of species life history and diet parameters can have three phases; the first aims to adjust weights-at-age and abundances to prevent extinctions, then to fine-tune weights-at-age, and finally to further calibrate biomass, matching estimates of unfished biomass where appropriate by adjusting recruitment and mortality parameters. During the second phase of calibration, the model is tested under varying degrees of fishing pressure to evaluate responses of functional groups when perturbed. The aim is to verify that the simulated groups are as productive and resilient as suggested by other analyses and field observations. Finally, the model's ability to replicate historical biomass trends under historical fishing pressures is evaluated.

## Data requirements for Atlantis

- Abundance per age class per area
- Consumption rates
- Diets
- Individual growth rates, length-weight conversions
- Max age, and age-at-maturity
- Recruitment parameters (e.g. Beverton Holt, Ricker, constant)
- General habitat preferences
- Dispersal and/or migratory characteristics, within and outside model
- Sediment/rock type per spatial box
- Biogenic habitat
- Abundance and catch time series (from monitoring program)

## Selected Atlantis references


Ainsworth, C.H. I.C. Kaplan, P.S. Levin, R. Cudney-Bueno, E.A. Fulton, M. Mangel, P. Turk-Boyer, J. Torre, A. Pares-Sierra and H. Morzaria Luna. Atlantis model development for the Northern Gulf of California. NOAA Technical Memorandum NMFS-NWFSC-110, 313 p.

Brand, E. J. , I . C. Kaplan, C. J. Harvey, P. S. Levin, E. A. Fulton, A. J. Hermann, J. C. Field. 2007. A spatially explicit ecosystem model of the California Current's food web and oceanography. NOAA Technical Memorandum NMFS-NWFSC-84, 145 p.

Horne, P. , I . C. Kaplan, K. Marshall, P. S. Levin, C. J. Harvey, A. J. Hermann, E. A. Fulton. 201 0. Design and parameterization of a spatially explicity ecosystem model of the central California Current. NOAA Technical Memorandum NMFS-NWFSC-1 04, 140 p.

Fulton, E. A., A. D. M. Smith, and C. R. Johnson. 2004. Biogeochemical marine ecosystem models I: IGBEM–A model of marine bay ecosystems. *Ecological Modelling*, 174:267–307.

Fulton E.A,. J.S. Parslow, A.D.M. Smith and C.R. Johnson. 2004b. Biogeochemical Marine Ecosystem Models II: The Effect of Physiological Detail on Model Performance. *Ecological Modelling*, 173: 371-406.

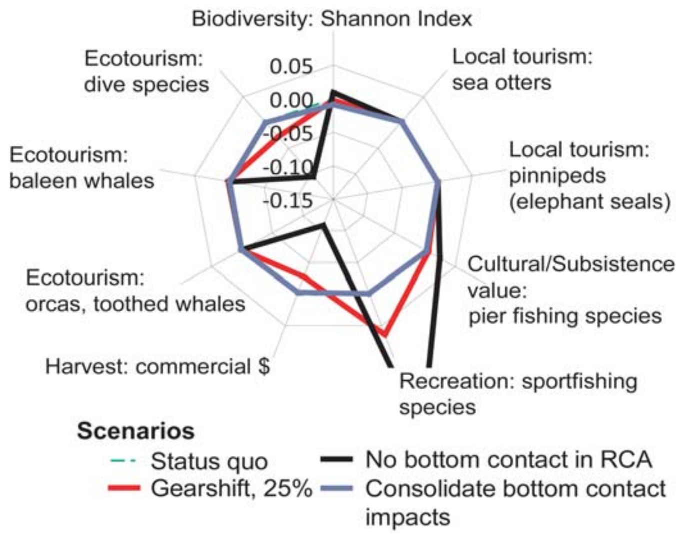
Fulton, E.A., Link, J.S., Kaplan, I.C., Savina-Rolland, M., Johnson, P., Ainsworth, C.H., et al. (2011). Lessons in modelling and management of marine ecosystems: The Atlantis experience. *Fish Fisheries*, 12:171–188.

Kaplan, I .C., P.S. Levin, M. Burden, E.A. Fulton, A. 2010. Fishing catch shares in the face of global change: A framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries and Aquatic Sciences,* 67: 1968-1982.

Kaplan I.C. and P.S. Levin. 2009. Ecosystem based management of what? An emerging approach for balancing conflicting objectives in marine resource management.In R.J. Beamish and B.J. Rothschild, eds. The Future of Fisheries In North America. Springer, NY 736 pages

# **Case Study 1** - Trade-offs between management scenarios have distinct effects on ecosystem services

Kaplan, I.C., P.J. Horne, and P.S. Levin. In review. Screening California Current fishery management scenarios using the Atlantis end-to-end ecosystem model

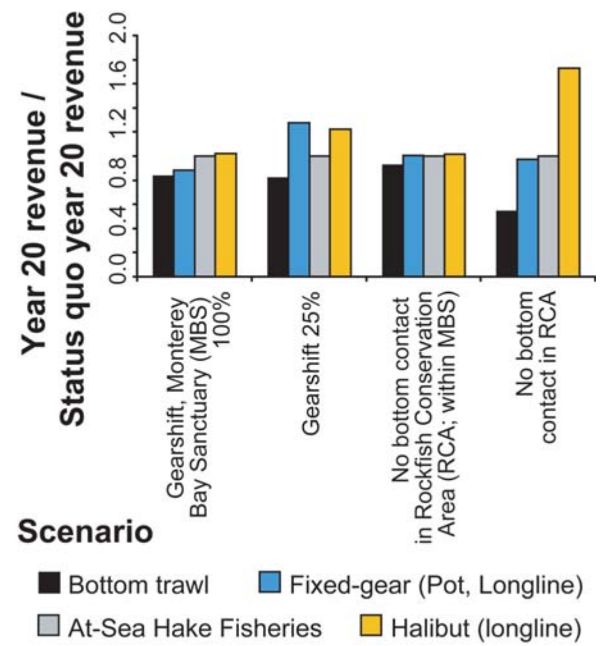



Performance of scenarios that involved large management changes at the coast-wide scale, relative to nine metrics. Scores for each metric have been normalized by performance in Status Quo.

Collaborative work with fishery managers at NOAA's regional offices and staff at the National Marine Sanctuaries (NMS) allowed a strategic exploration of broad fishery management options on both groundfish and ecosystem services in the California Current.

We examined status quo management and 20-year projections of several gear switching and spatial management scenarios, using an Atlantis ecosystem model. These scenarios involved changes to Rockfish Conservation Areas, Essential Fish Habitat, the amount of trawling relative to other gears, and overall levels of fishing effort, both at a coast wide scale and within Monterey Bay National Marine Sanctuary. The scenarios were evaluated in terms of their ecological and economic performance, with a focus on metrics of ecosystem services, groundfish, and ecosystem health.

No single scenario maximized all services — all involved trade offs. At the coast-wide scale, the strongest trade offs were between abundance of recreational targets vs. commercial harvest and prevalence of fish species preferred by divers. Local gear shifts and spatial management within MBNMS did lead to increases in some services, but only if the impact was measured at this local scale. Economic costs within the Sanctuary that were associated with some of the improvements in ecological performance were highest when the management actions only involved the sanctuary, and were minimal when the management action occurred at a coast wide scale. The scenarios involved winners and losers among both fleets and species. For instance, there were direct impacts of the scenarios on fleets, such as trawl and longline+pot fleets, as well as indirect effects such as gains to the halibut longline fishery when trawl effort declined.




Revenue of four fleets under alternate scenarios, based on 20 year projections

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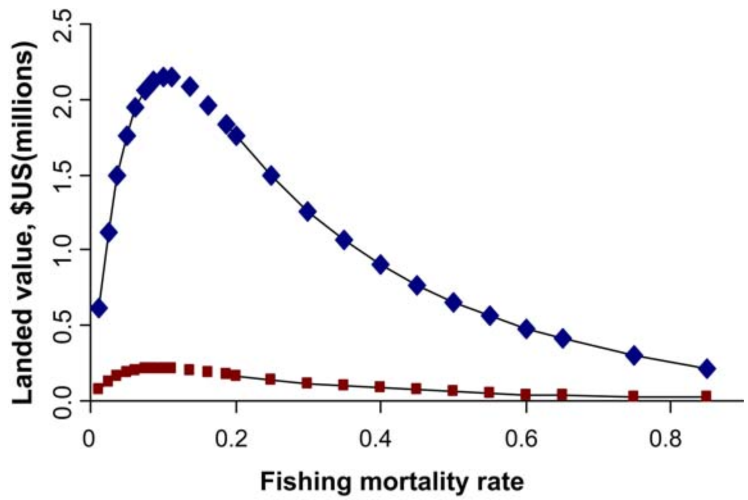
# Case Study 2 - Ocean acidification effects on the foodweb are mediated by predator/prey response

Kaplan, I.C., P.S. Levin, M. Burden, E.A. Fulton, A. 2010. Fishing catch shares in the face of global change: A framework for integrating cumulative impacts and single species management. Canadian Journal of Fisheries and Aquatic Sciences 67: 1968-1982

Projected increases in $CO^2$ levels as a result of global climate change could lead to 1.8 - 4°C increases in sea surface temperature and declines in pH of 0.14-0.35 or as extreme as 0.3-0.5, from a current level of ~ pH 8.1. Reductions in pH of this magnitude could lead to mortality of shell-forming corals, benthos, and plankton groups due to reduced calcification rates in an acidic ocean. Using an Atlantis ecosystem model for the US West Coast, four scenarios were developed for future catch (landings + discards) that reflect likely fisher behavior under the new incentives and flexibility expected with Individual Fishing Quotas (IFQ) for the US West Coast groundfish trawl fleet.




Landings of English sole under various fishing mortality rates (x-axis) with current ocean conditions (top line) vs. conditions with strong effects of acidification on shelled benthos (bottom line). English sole exhibited a tenfold decline in potential catch and economic yield when confronted with strong acidification impacts on shelled benthos.

Fishery management schemes, such as IFQs or marine protected areas, should be designed to be robust to potential shifts in the biophysical system, such ocean acidification. Possible catch scenarios were coupled with ocean acidification through increased mortality of benthic shelled organisms and plankton. This study is an example of how Atlantis can be integrated with established management reference points and decision mechanisms. Atlantis can capture indirect effects related to shifts in predation, which are not represented in single species assessment models.

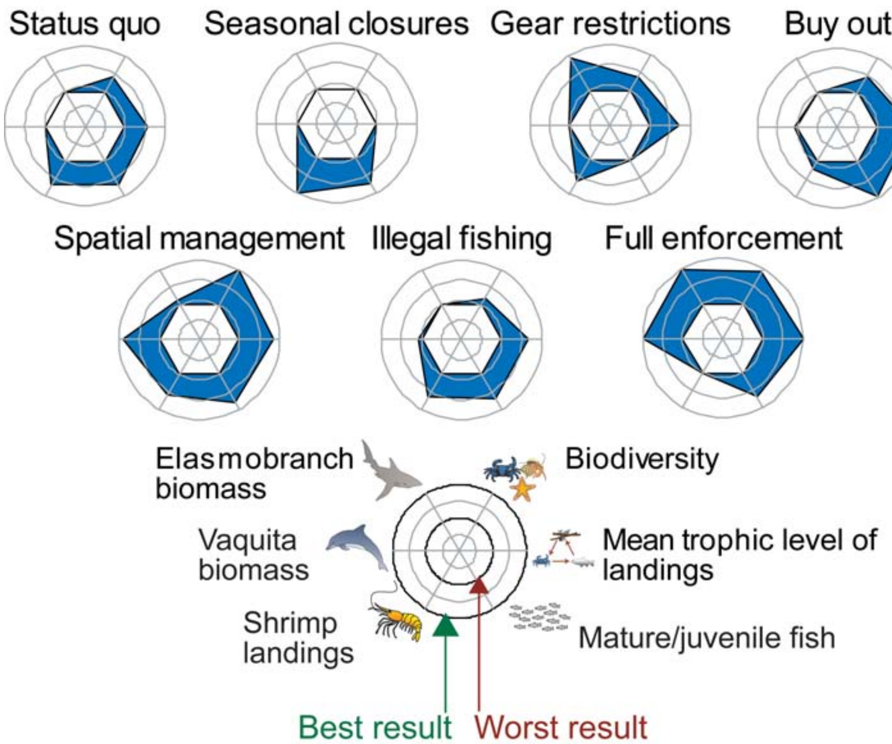
IFQ harvest scenarios alone in most cases did not have strong impacts on the food web, beyond the direct effects on harvested species. However, when the impacts of ocean acidification were added, the abundance of commercially important groundfish such as English sole (*Pleuronectes vetulus*), arrowtooth flounder (*Atheresthes stomias*), and yellowtail rockfish (*Sebastes flavidus*) declined 20-80% due to the loss of shelled prey items from their diet.

Therefore IFQs should be complemented with careful consideration of potential global change effects, active monitoring for such effects, and adaptive policies to adjust catch limits if ocean acidification or other environmental changes begin to drive underlying population dynamics.

# **Case Study 3** - Compliance with existing fisheries regulation yields ecological benefits

Ainsworth, C. H. Morzaria-Luna, I .C. Kaplan, P. Levin, and E. Fulton. 2011. Full compliance with harvest regulations yields ecological benefits: Northern Gulf of California case study. Journal of Applied Ecology. doi: 10.1111/j.1365-2664.2011.02064.x

Fishery policy in Mexico has attempted to address resource overuse. Unfortunately, compliance with existing regulations is poor; illegal fishing and poaching are widespread and few fisheries respect seasonal closures. Atlantis was used to estimate the benefits of compliance with existing fisheries regulations in the Northern Gulf of California, including spatial management, seasonal closures, gear restrictions, removal of illegal fishing, buyouts and programs to encourage gear switching, and the combination of these regulations into 'full enforcement'.




Radar plots of socioeconomic and ecological benefits for each scenario in terms of six metrics. The results are scaled to show the worst and best results observed. The range in between shows the scope of possible outcomes. No one regulatory instrument was able to address all major conservation and fishery concerns.

Spatial management protections, including marine protected areas, concessions, seasonal closures, and effort reductions, improved the quality of breeding, feeding and refuge space, assisted in the recovery of predatory fish and the endemic porpoise, and efficiently preserved ecosystem biodiversity due to the wide umbrella of protection offered across ecological communities.

However, no single instrument provided the combined protections offered by the full enforcement scenario. Full compliance (enforcement) improved economic efficiency for fisheries, increased ecosystem biodiversity, and improved recovery potential for depleted species, both commercial and charismatic. Under a full compliance scenario, there were large increases in protected species biomass within 25 years and a slowed rate of ecosystem degradation due to fishing. Full compliance costs the fishing industry about 30% of its annual revenue, with greatest losses occurring in the offshore pelagic gillnet fleet.

Improving compliance with existing fisheries regulations through approaches such as improved education, monitoring and enforcement, could have positive ecological benefits and be immediately applicable under the current regulatory regime.

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